

If cannons cannot fight hail, what else ?

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Abstract. Hail suppression is an uncertain meteorological subject in premature agricultural servitude. Commonly known is the method of seeding menacing cumulonimbus clouds with silver iodide by means of rockets or aircraft flares. Less discussed but widely practised alternatives are also reviewed here, in particular the useless but still quite popular practice to attempt destroying hailstones with explosives or with sound blasts from so-called hail cannons. The state of the art of hail formation detection with radar, and of hailfall probability nowcasting, is briefly reviewed.

Zusammenfassung. Hagelabwehr ist ein unsicheres meteorologisches Thema, das jedoch in der Landwirtschaft leichtfertig angegangen wird. Eine allgemein bekannte Methode impft Cumulonimben mit Silberjodid, das mit Raketen oder Flugzeugen eingebracht wird. Im vorliegenden Aufsatz werden auch weniger bekannte, aber dennoch häufig angewandte Methoden vorgestellt, ins Besondere das wirkungslose, aber recht beliebte Verfahren, dass man versucht Hagel zu bekämpfen durch Sprengstoffe oder durch den Knall sogenannter Hagelkanonen. Darüber hinaus wird der heutige Stand des Wissen zum Erkennen von Hagelentstehung mittels Radars und zum Nowcasting der Eintrittswahrscheinlichkeit von Hagel dargestellt.

1. Generation and occurrence of hail

Hail is a disaster for everybody, but particularly for farmers. We can try using magic or prayer to keep it away (MORGAN, 1973), or else consider it as an occasional stroke of fate. Because hail is incidental in space and time, we can spread the risk and insure ourselves against its damage. However, for farmers of soft crops the damage is already noticeable for relatively small-sized hail, so their risk is relatively large and their insurance premiums are high. This spurs those farmers to action.

The zero option of action is to cover low crops with nets. That influences the crop climate, though not as badly as rumoured. Also there are problems of mounting the nets and of reduced accessibility to the crop (VAN ARKEL, 2003). However, using nets means that hail occurrence is passively accepted as a fact of nature. But many do not accept this and try to prevent hailfall.

If we want to try preventing the falling of large hail, we first must see how and when such hail is formed. The following simplified description of hail generation contains most major basic features, referring for more extensive information to more complete reviews such as RAKOVEC (1989) and KNIGHT and KNIGHT (2001).

Hailstones develop in high cumulonimbus clouds, which form if the temperature difference between the earth and the upper air is very large. Then the air at the surface is unstable and will rise in an updraft, and it cools while rising so that the water vapour in the air will condense on any suitable tiny nucleus of matter. However, at temperatures above -40°C cloud water drops will not freeze unless also particles with an ice-like surface structure are present, so-called freezing or ice-forming nuclei, either natural, or PbI₂ or AgI. Then at temperatures below -4°C the freezing can begin.

A newly formed piece of ice cannot become a large hailstone unless it is carried in the cloud by an updraft which is just a little bit stronger than its falling speed. If the updraft is too strong, the young hailstone will be blown out of the cloud top into the "anvil" of the cloud, and if the updraft is too weak the hailstone will fall before it has grown. But if the ice can remain at a temperature level of -10°C or less, typically around 5 km height, the ice lump will attract the water from the liquid drops around, either by collision or by differential vapour transport.

So for generating hailstones, which are large enough to reach the warm earth without melting while falling, a cloud must have both weak updrafts for the just-formed small hail and also a strong updraft to carry the stones of grown size. Large hail is only formed when cumulonimbus clouds are large enough to have a complex cell structure of the right strength. The diameter of a hail-forming cumulonimbus is of the order of 10 km, and the diameter of the strong updraft where the big stones are growing is of the order of 1 km. Such a cumulonimbus usually travels along with the airflow at ≈ 4 km height with a speed of 30-60 km/hr. In open country this means that large hail usually falls in narrow strips of ≈ 1 km width and a length of several km, depending on storm strength. In mountainous country the hailstorm may travel less and then drops much hail on a limited area.

In summary, generation of hail requires: (1) humid air in the surface boundary layer as source of water for the cloud updraft; (2) sufficient atmospheric instability to form cumulonimbus clouds of big size and great strength; (3) freezing temperatures above the boundary layer; (4) ice-forming nuclei in the right amount; and (5) at least an hour of hail growth time.

Only the fourth condition, nuclei, is accessible for human action. The first three conditions depend on local climate and actual weather, and they show why hail is a midlatitude problem: at high latitudes large instability occurs seldom, and tropical clouds are warm. Moreover mountainous regions generate upslope flow and so have relatively high hail risks. In Europe therefore the interest in possibilities of hail prevention is strongest in central and southern Europe (Fig. 1).

2. Detection of hail by radar and forecasting of hail

A good forecast of actual hail probability is needed to start defensive preparations, both by covering up glasshouses and other breakables and maybe by starting some action. When actually cumulonimbus clouds are approaching, then it is useful to find out whether they are indeed likely to produce hail. Radar is useful to sense hail-generating power of clouds, and radar performance has increased significantly lately.

Nowadays, the most direct way to detect hail is by using a so-called dual-polarization radar. This type of radar can make a direct distinction between the oriented oblate raindrops and the hailstones with an isotropic orientation distribution (BRINGHI and CHANDRASEKAR, 2001). Unfortunately, the vast majority of the operational weather radars in Europe still uses single polarization (about 150 radars), and so far only a few dual-polarization radars have been installed. Hail detection methods for operational use thus have to rely on single-polarization radar data, possibly complemented with data from other sources.

A comparison of eight different hail detection methods for single-polarization radar has been done in the Netherlands. Hail observations of 15 thunderstorm days in 1999 from an extensive network of 321 volunteers and hail damage reports from three different agricultural insurance companies have been used for verification (HOLLEMAN et al., 2000). It was found that the hail detection method which Waldvogel developed for hail suppression experiments in Switzerland performed best (WALDVOGEL et al., 1979). This method to detect developing hail by radar uses as indicator for presence of substantial updrafts the vertical extension ΔH of a strong reflectivity core (> 45 dBZ) above the freezing level below (see Fig. 2). The actual strength of the reflectivity core can be used to gauge the amount of supercooled water and ice.

The Probability-Of-Hail (POH) of all hail sizes for a horizontal position tolerance of 12.5 km, as determined from ground-reference data of the summer of 2000 corrected for unobserved showers, appears to be proportional to Waldvogel's ΔH over a wide range (Fig. 3). The following regression formula is found:

$$\text{POH} = 0.319 + 0.133 \Delta H$$

with ΔH in km. Using this as calibration formula, together with freezing level data from a numerical weather prediction model like HIRLAM (UNDEN, 2002), a warning map with POH estimates is generated operationally from real-time radar observations (HOLLEMAN, 2001).

A further assessment of uncertainties in radar echo top heights and their impact on the derived probability of hail has been performed, based on a comparison of vertical cross-sections extending between two radars (DELOBBE and HOLLEMAN, 2006). It was found that the effective range for hail detection should be limited to 160 km and that the small errors in the reflectivity may strongly affect the derived POH.

Nowcasting of severe weather events, including damaging hail, is generally done by extrapolation of weather radar echoes (WILSON et al., 1998). For extrapolation of weather radar echoes the (average) motion of the echo pattern must be determined from a series of radar images. The motion vectors can be determined and extrapolated either by the cross-correlation technique (TREC, see LAROCHE and ZAWADZKI, 1995) or by tracking of individual convective cells (TITAN, see DIXON and WIENER, 1993). Actually a few algorithms, e.g. NIMROD (GOLDING, 1998), use wind vectors from a numerical weather prediction model to extrapolate radar echoes.

The straightforward extrapolation schemes rely on the assumption of steady-state or Lagrangian persistence, where the size and intensity of the radar echo pattern is not changed during the extrapolation. The usefulness period of such extrapolations of atmospheric structures is limited by half their Lagrangian lifetime, increasing with scale size (STULL, 1985). For individual thunderstorm cells the lifetime is very short and their predictability decreases very rapidly during the first 30 minutes. Development and motion of larger organized features, like squall lines and supercell storms, can be reasonably well forecast for periods of a few hours by extrapolation.

Observed trends in echo size and intensity can be used to (try to) improve the forecasts based on extrapolation. The nowcasting method dubbed GANDOLF (PIERCE et al., 2004) even includes conceptual life cycle models of single-cell, multi-cell, and supercell thunderstorms. Other methods use smoothing or filtering of the extrapolated echo patterns to suppress small-scale features with short lifetimes (GERMANN and ZAWADZKI, 2002). Unfortunately, many severe weather events like damaging hail and rain are associated with small-scale features and thus have a bad predictability.

During the Olympic Games in Sydney 2000 the performances of six severe weather detection algorithms and five nowcasting systems were evaluated simultaneously (JOE et al., 2004). The majority of the systems generated nowcasts with a maximum range of 60 minutes and the performance statistics were evaluated for 30 minute forecasts. The methods based on cell tracking provided more reliable extrapolators of showers and other small-scale features, but the exact position and time of single thunderstorms were not predictable (PIERCE et al., 2004).

For longer forecasts numerical weather prediction (NWP) models should be used, possibly combined with model output statistics (MOS). Models with a high spatial resolution and a rapid update cycle, like HIRLAM (UNDEN, 2002), are best suited for prediction of (severe) convection. Assimilation of radar data in limited area models potentially improves the short-term skill of a model (ALBERONI et al., 2003), but that is currently done in a few operational models only. Models can provide an indication of the possibility of severe weather a few days ahead, but the exact location and time of the event are usually not accurately forecasted.

Summarizing, extrapolation of radar data can provide a reliable forecast of severe convection and/or hail up to a few hours ahead only for mesoscale organized cloud systems, certainly not for solitary thunderstorms. Claims of hail cannon manufacturers, that purchase of their simple radar units allows weather amateurs to make reliable hail forecasts for 95% of the time, are meteorological nonsense.

3. Brute-force fighting of hailfall

Assume that hail showers are imminent. Then people desperately want to ward off their danger, and two active approaches are then possible. A modern approach is to try influencing the hail formation process by seeding the clouds with freezing nuclei. Let us discuss first the more classical approach, namely the use of brute force in an attempt to weaken or to destroy the formed hailstones.

An obvious technique to try is to destroy the hail by way of explosions. It was suggested by RUBY (1953) and VITTORI (1960) that shock waves might make occasional air bubbles in hailstones collapse, making the stones mushy. Italrazzi-type anti-hail rockets (Fig.4) then were developed to deliver explosive charges of about 1 kg TNT in the lower part of clouds, where the falling hailstones are. Such rockets became very popular in Italy, China, Kenya and the Balkan (NEYMAN and SANSOM, 1966; MORGAN, 1973; MORGAN, 1984). The rockets are generally launched when hail begins to fall, and it is claimed that after some time the hailfall decreases and the clouds disperse.

However, it is known that hail takes about 5 minutes to fall, and that the largest fall is at the beginning of the hailstorm. In other words, observed improvement may well be due to the natural end of the hailstorm and not really caused by the rockets (SULAKVELIDZE et al., 1965). It was claimed that such explosions destroyed hail within a 400 m radius, but laboratory experiments by LIST (1963), by FAVREAU and GOYER (1967) and by an Italian team showed that explosion of 1 kg TNT hardly affected hailstones within a 10 m radius. In the field, Blaserna and Marazzi earlier had shown that 250 rockets, each carrying 8 kg of explosives, had no effect on hailfall (PERNTER, 1907). Figuring how many hailstones are present in a single cumulonimbus and how big such a cloud is, a Russian meteorologist calculated that 100000 rockets would be needed to affect a single cloud noticeably. In regions like the French Provence the use of rockets is nearly abandoned now.

In short, the only beneficial effect of firing explosive rockets and grenades at hailclouds may be the emotional satisfaction of the gunners, who have fired at the enemy. In Italy, three-quarters of those who are still gunning are happy with their action, though its effectivity was never proven.

Next to rockets, hail cannons are the best known apparatus to fight hail by force. They direct the sound of an acetylene explosion, more than 120 dB, upward by way of a conical vertical muzzle. Originally these cannons were developed in 1896 by Albert Stiger, an Austrian winegrower. When in Stiger's valley no hail had fallen for two years, employing these cannons became an immense craze in Austria and in northern Italy. A cannon industry developed, and over ten thousand cannons were employed in the region around 1900. At a hail conference in Lyon in 1901, many different makes of cannon were offered for sale (Fig.5). However, when regularly locations with plenty of cannons were heavily damaged by hail, public confidence decreased and the authorities organized a systematic experiment of several years in some Austrian and Italian regions. By the time that this experiment was concluded in 1906, most farmers already had sold their useless cannons as scrap iron (PERNTER, 1907; ODDIE, 1965; CHANGNON and IVENS, 1981).

However, people who do not know history are doomed to repeat it. In 1972, the French company Corballan began again to manufacture the Stiger hail cannon, and gradually it became popular again. Presently these cannons are produced in Spain, Canada and Belgium (Fig.6). In Italy, France, Austria, the Netherlands, the United States, Australia, New Zealand and Tibet these cannons were sold unscrupulously to a willing public of farmers, who have suffered hail damage and want to take action against it. The cannon is a large impressive apparatus (Fig.7), it makes a lot of noise, and it comes with confidence-building detailed instructions. Possible advisors, like meteorologists or agricultural consultants, cannot say for sure that it does not work, because existing investigations of cannon uselessness were never published accessibly (W.R. Cotton, pers. comm., 2005). Our aim is to do so now, using several quantitative studies which were reported acceptably.

In 1902, the regions Castelfranco Veneto and Windisch-Feistritz were each armed with some 200 hail cannons. These were placed in part of these regions, closer together than even suggested by directions of hail gun merchants, and were used intensively. The leader of this Austrian-Italian project, Blaserna, said in his final report that in 1902 often the areas with cannons had more hail damage than those without, and the same negative effect was observed in 1903 and 1904. Meanwhile the farmers' devotion to the use of hail cannons had changed into disapproval, and Blaserna stated: "at the end of 1904, I could say without exaggeration that I was the only one still shooting at clouds". So the Accademia dei Lincei in Roma concluded that hail cannons were failures (PERNTER, 1907).

In the Italian province Ferrara, 49 cannons were used in 1982 (BENINCASA et al., 1991). During that year hail damage occurred in 21% of the entire provincial area (Fig.8). Hail fell in 22% of those locations which were fully protected by cannon action, and also in another six marginally covered locations. It follows that in Ferrara the use of cannons did not really ward off hail.

In Val di Non, Italy, 12 cannons with guiding radar were placed in an area of 10 km², and used in cooperation with meteorologists supported by an existing hailpad network. During 1981 and 1982, annual hail damage in the valley was similar to what it had been in 1973-1980. Moreover there was no significant difference in damage between the "protected" area with cannons and the areas without cannons (FERRARI and PAOLETTO, 1982). The cannons were scrapped.

Manufacturers of hail cannons quote in their sale leaflet (Fig.6) as official proof of cannon effectiveness an experiment in the Emmental valley, Switzerland. That experiment was done by the Fruit Culture Station in Oeschberg, and their full results are summarized in Table 1. Unfortunately, no hailpads were located at shorter distances from the active hail cannon than 400 m, and local hailfall tracks were not documented. For these and other reasons the Swiss investigators judged their results to be inconclusive (MAURER, 1987). Most cases show some trend with distance, but that could well be an orographic effect.

The hail cannon sale leaflet quote is unacceptably selective: it lists only the first two observed single showers, named "year 1981" and "year 1983" -- suggesting averages of full years of observation. The leaflet claims success because "not a single hailstone has fallen within 500 m distance from the hail cannon". The other seven evaluated showers, where no great decrease of hailfall is observable at 400 m distance, are not mentioned at all in the leaflet. This is a clear case of scientific cheating.

In summary, it may be concluded from all field data (Castelfranco Veneto, Windisch-Feistritz, Ferrara, Val di Non and Emmental) that the use of a hail cannon has no significant effect on hailfall.

Laboratory tests of cannon action are also negative. As mentioned above, it was proved that rocket explosions at cloud height are ineffective to destroy hailstones. Thunder has no known effect either. It follows that surface-emitted sound waves, simple and less forceful, will be even less effective -- except maybe to annoy the neighbourhood. A pressure shock of the order of 300 hPa is needed to impress a hailstone containing cavities; the cannon shock was measured to be 1.3 hPa at 100 m distance. It was claimed that the hail was made mushy and soft by the cannons, but hail comes in many varieties and can be mushy from nature (MASON, 1975; RASMUSSEN and HEYMSFIELD, 1987). In an experiment in France by Mezeix, the cannon was placed horizontally and hailstones were hung in front of it at distances up to 100 m. At no distance any damage to the hailstones by the cannon sound wave was observed (FERRARI and PAOLETTO, 1982).

Cannon instructions suggest various fancy theories, for example that the shock waves are reflected by the clouds and in meeting rising waves are ionising air, thereby changing the physical behaviour of the cloud above in an unspecified important manner. Such arrant nonsense may sound impressive to the scientific layman. However, the official judgement of the World Meteorological Organization on these unfounded fancy ideas is clear: "In recent years, anti-hail activities using cannons to produce loud noises have re-emerged. There is neither a scientific basis nor a credible hypothesis to support such activities." (WMO, 2001).

4. Seeding the clouds to prevent large hail.

We can conclude that brute force methods, rocket explosions and cannon sounds, are no effective protection against already formed hail. If we still want action, the alternative way is to influence the hail formation process by seeding the clouds with hygroscopic or ice-forming nuclei. Instead of overrating our puny power, which can not possibly compete with the gigantic masses of energy and material in a cumulonimbus cloud, we try to make the cloud do the work by tickling it effectively.

There are various possible seeding strategies which are being pursued, of which the most promising are beneficial competition and early rainout (COTTON and PIELKE, 1995; WMO, 1996). Early rainout is induced by hygroscopic seeding in the weak updraft region of the cloud. Other seeding strategies, like cloud water glaciation or trajectory lowering, are either impractical by requiring much too much seeding material, or else are still in too-early stages of investigation. Here we prefer an engineers approach, namely identifying hail suppression approaches that are based on plausible physical principles and also appear to work in practice — even though they are not fully understood and experimental proof is still limited.

Beneficial competition is based on the assumption that the water volume V in a cloud is limited, and if that water is divided equally over N precipitation elements, then the radius r of these elements follows from $N \cdot r^3 \approx V$. By injecting many extra ice-forming nuclei into the cloud at the right time and at the right place, where in weak updrafts hail formation is beginning, it should then be possible to reduce the average size of fully-grown hailstones. Small hailstones may melt on the way down and are less damaging anyway. Used amounts of silver iodide (AgI) are not large and are estimated to produce no serious ecological side-effects (BORLAND and CHANGNON, 1977; DESSENS, 1998).

Proving the success of rain enhancement or hail diminishment methods is quite difficult, primarily because precipitation is climatologically extremely variable. In mid-latitudes the occurrence of several years with little hail or rain is common, and these droughts may be followed by years with much precipitation (Fig. 9). Therefore validation of precipitation modification methods requires experiments lasting five to ten years, and in particular for convective precipitation such as hail the experiments should be randomized in time and space. This last requirement is usually not very acceptable for a farming community which, assuming that the method might work to their profit, wants its application to be everywhere and continuous. Often farming communities have a strong voice in matters of public finance, and then setting up a randomized experiment of long duration is hardly feasible.

Measurement is also a major problem in precipitation experiments. High observation network densities are required, at least a factor 10 denser than for other meteorological parameters. Moreover automatized hail measurement does not exist, and a hailpad network is a laborious and costly undertaking. Often then hailfall is estimated from records of agricultural damage and insurance claims, but that is not reliable (WMO, 1986). For example, crop damage is not always correlated with the surface-measured hailfall area or hailfall mass, partly because heavy rain and wind are damaging too. Moreover, in different regions the crop damage assessment is done in different ways and at different phenological times. Insurance practices vary between nations. Also coverage may be related to hypes rather than to reality: if everybody bought a cannon and terminated his hail insurance, claims would cease so "insurance-proven" cannon efficacy would be 100%.

Only two seeding approaches have been operationally applied to such a large extent that it is possible to quantify their present practical usefulness somewhat, and to gauge costs of equipment and required organization. Both are based on beneficial competition. We will identify them by the names of their originators, Sulakvelidze and Dessens, and describe them concisely.

Four nuclei injection methods are possible (Fig.10). The Sulakvelidze approach is to inject the nuclei directly into the upper cloud region where the hail develops, typically about 1 km³ at 5 km height. In Russia and in Eastern Europe, SULAKVELIDZE et al. (1965) sent Oblako rockets or

artillery grenades loaded with AgI into the hail formation region of the cloud. Operations of this type are a major undertaking, because radar technicians and cloud-wise meteorologists are needed to indicate when and where to send the nuclei, and also artillery personnel must be available to fire the rockets accurately at the right time. Governmental organization and financing are required to set up local radar-equipped centres (MARWITZ, 1973). Success of over 50% hail diminishment was claimed.

In the U.S.A. official permission for such artillery is difficult to obtain, so there airborne AgI delivery was developed. Either aircraft above the cloud dropped AgI flares into it, or else aircraft flying below the clouds were equipped with AgI burners. In the last option, delivery of nuclei to the upper part of the cloud is entrusted to the cumulonimbus updraft. The U.S. success was decidedly less than in Russia, and it was not clear whether this was due to local differences in hail formation processes or to delivery methods (SCHLEUSENER, 1968). Hail suppression by seeding is continued in the U.S.A., its results are still uncertain (KRAUS, 1999; LIST, 2004).

Around 1980 a large experiment was organized in Switzerland with French and Italian support, Grossversuch IV, using Russian-style rocket delivery with sufficient randomization. The outcome of this experiment was not encouraging: in 205 seeding cases the seeding produced only 5% less risk (FEDERER et al., 1986; VENTO and DAMIANI, 1987). Nevertheless, the Sulakvelidze method is used operationally in many countries across the world (WMO, 1996; ABSHAEV, 1999), and attempted evaluations indicate that in suitable climates the hail damage reduction might be 15% to 20% (MESINGER and MESINGER, 1992). However, use of operational data only is unlikely to result in plausible validation (RAKOVEC et al., 1990; POCAKAL and STALEC, 2003).

The Dessens approach to beneficial competition is not selective precision delivery of nuclei into particular clouds, but rather raising the average concentration of nuclei in a limited region when a menacing cloud front is approaching. This is done by a surface station network with a typical mesh size of about 7 km (FEDERER, 1977; DESSENS, 1986). The stations burn AgI in acetone (Fig.11). Here again the delivery of nuclei at cloud top level is entrusted to convective updrafts, which works best if in the region the thundercloud bases are usually low.

Organization is therefore quite different from the Sulakvelidze approach. The national weather service (NWS) is involved to deliver a local forecast of general hail probability, four hours ahead, largely based on extrapolation of radar echoes and therefore most reliable for mesoscale squall lines. When such a forecast is given, a network of about a hundred local volunteer stations is alerted to start up their burners. Such surface-based seeding networks have been set up in southern France by ANELFA (National Association for Study and Suppression of Atmospheric Scourges; Fig.12), and in some other countries like Spain. The limited network costs are provided by regional government, so are dependent on politics.

In the nineties, the French network has been provided with hailpads to get more solid analysis of success rates, which is now claimed to be 16% to 30% hail damage diminishment, depending on the density and the extension of the nuclei generator network (DESENS, 1998). Possible persistence effects and the absence of a non-seeded control area complicate the analysis if and how this is achieved.

5. Conclusions.

In summary, for dealing with hailfall risks the use of cannons or explosive rockets is waste of money and effort. Seeding the clouds is a theoretically feasible method of hail suppression, but so far has not been supported by randomized experiments (LIST, 2004). Operational seeding evaluations, of which the reliability is dubious for various reasons (WMO, 1986), show uncertain results which vary by region.

The two operational beneficial-competition methods conform to different social systems. Application of Sulakvelidze's targeting of individual clouds is a centralized approach, requiring very large investment in radar equipment and in professional personnel. Application of Dessens's

surface-based method is more a matter of broadly supported volunteer action, with significantly lower costs but also requiring organization of a large network, as done e.g. in France. Dessens's approach cannot be applied by just a few enthusiasts or professionals.

Both seeding methods may only be cost-effective in particular climates for particular crops, therefore the consideration of their application requires serious homework (MAYBANK, 1977). Preparations should include meteorological advice and local research on the local cloudiness properties, because it is a truism that there is no such thing as a typical precipitation climate. Moreover, in planning any experiments it is wise to organize objective validation from the beginning onwards, and also social and environmental factors need attention (BORLAND and CHANGNON, 1977). Even so, if anywhere hail suppression by seeding is considered, significant success is not guaranteed.

Large hail can successfully be detected using weather radar networks, and a calibrated probability-of-hail can be derived from limited-area models and radar observations (HOLLEMAN et al., 2000). Forecasting of large hail based on radar is difficult because the lifetime of small-scale weather phenomena is rather short. The deterministic accuracy of forecasts based on extrapolated radar echoes of single storms decreases very rapidly during the first half hour. Only more organized cloud systems, like squall lines and supercells, can be successfully extrapolated for longer periods (WILSON et al., 1998). From NWP models with a high spatial resolution a useful indication of the probability of severe convection can be obtained a few days ahead.

Because hail is such a localized and incidental phenomenon, insurance remains a useful measure to compensate damage, unless the local risk is extremely high (FOSSE and CHANGNON, 1993). Determination of such risk requires knowledge of the hailfall climate, but hailfall data from surface station networks are seldom available (WIERINGA and LOMAS, 2001). Therefore it would be useful if existing radar networks built up a climatological database of hailfall probability maps based on the Waldvogel criterion.

Even in regions with only moderate hailfall, the damage risk for soft crops with a high value per area (e.g. fruit) may be so large that realistic insurance premiums become uneconomically high. In that case the safest strategy is placing nets above the crop, if feasible. Then agrometeorological aspects must be considered, such as the effect of approximately 10% irradiation decrease, or frost problems. It might be useful to investigate net climate in analogy to glasshouse climate.

Overall, the question whether hail suppression is feasible is emotionally loaded by the fact that the damages to crops, or cars, can be so disastrous. We can acknowledge humbly that the forces of nature can exceed by far the forces of man, either by covering vulnerable objects insofar possible or by taking insurance. For some stricken parties such a defensive attitude will always be less satisfactory than the acquisition of useless artillery, with which they can do something.

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Tables

Table 1. Average hailfall (hits per dm²) in nine hail showers, as observed by a network of 21 hailpads (12 dm² each) positioned in all directions at distances of 400 to 2000 m from a working Corballan hail cannon in Grosshöchstetten, Emmental. In 1980 and 1982 no hail fell locally. A very heavy hail shower on 7-5-1986 destroyed temporarily the hailpads. (MAURER, 1987).

Date (day-month-year)	Type of hail	Hailfall averaged over all directions at distance of			
		400 m	600 m	1000 m	2000 m
9-8-1981	hail	0	1	11	40
4-7-1983	graupel	0	1	30	62
7-6-1984	graupel	115	113	199	205
31-7-1984	hail	31	32	51	72
4-8-1984	graupel	46	47	53	48
19-5-1985	heavy hail	27	26	30	37
18-8-1985	hail	28	42	61	55
26-5-1986	light hail	24	22	33	48
21-8-1986	light hail	72	100	65	205

Figures and Captions



Fig. 1 Major hail risk area in Europe (BERZ and SIEBERT, 2000)

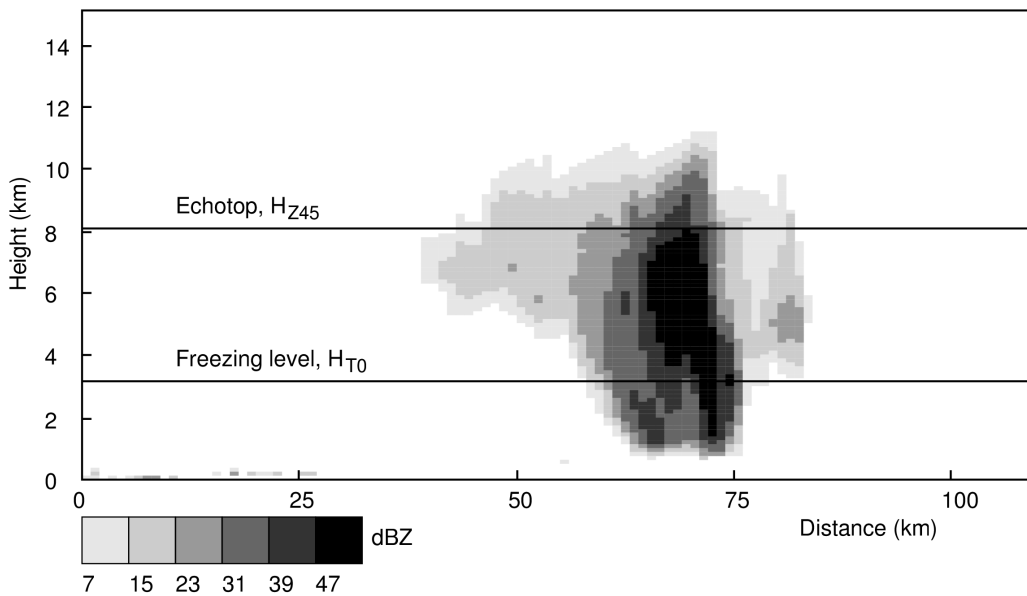


Fig. 2 Vertical cross section through a thunderstorm as observed by C-band weather radar. Waldvogel hail algorithm parameters are indicated.

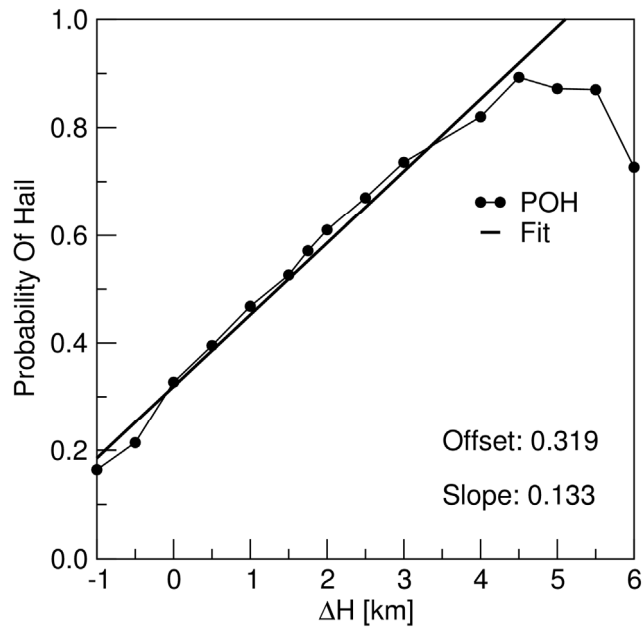


Fig. 3 Hailfall probability, estimated from observations and damage reports in the summer of 2000, compared with Waldvogel's radar threshold parameter ΔH .



Fig. 4 Italrazzi exploding rocket, ready for launch (MORGAN, 1984).

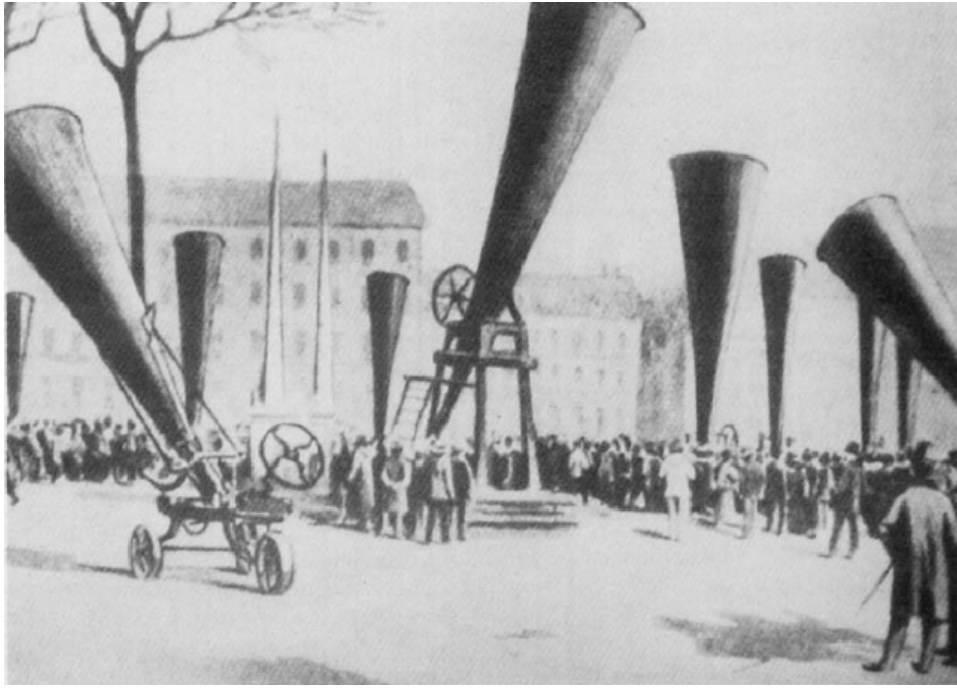


Fig. 5 Hail cannon market at 3rd International Congress on Hail Shooting, Lyon 1901 (CHANGNON and IVENS, 1981).

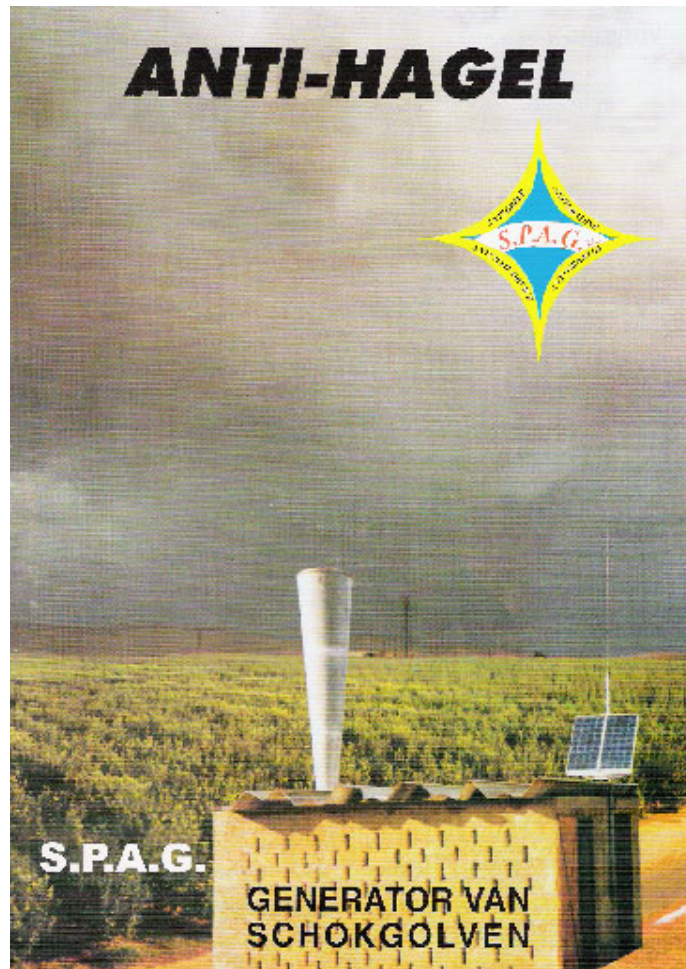


Fig. 6 Sale leaflet of hail cannon factory, 2001.



Fig. 7 Hail cannon in orchard at Krabbendijke, the Netherlands.

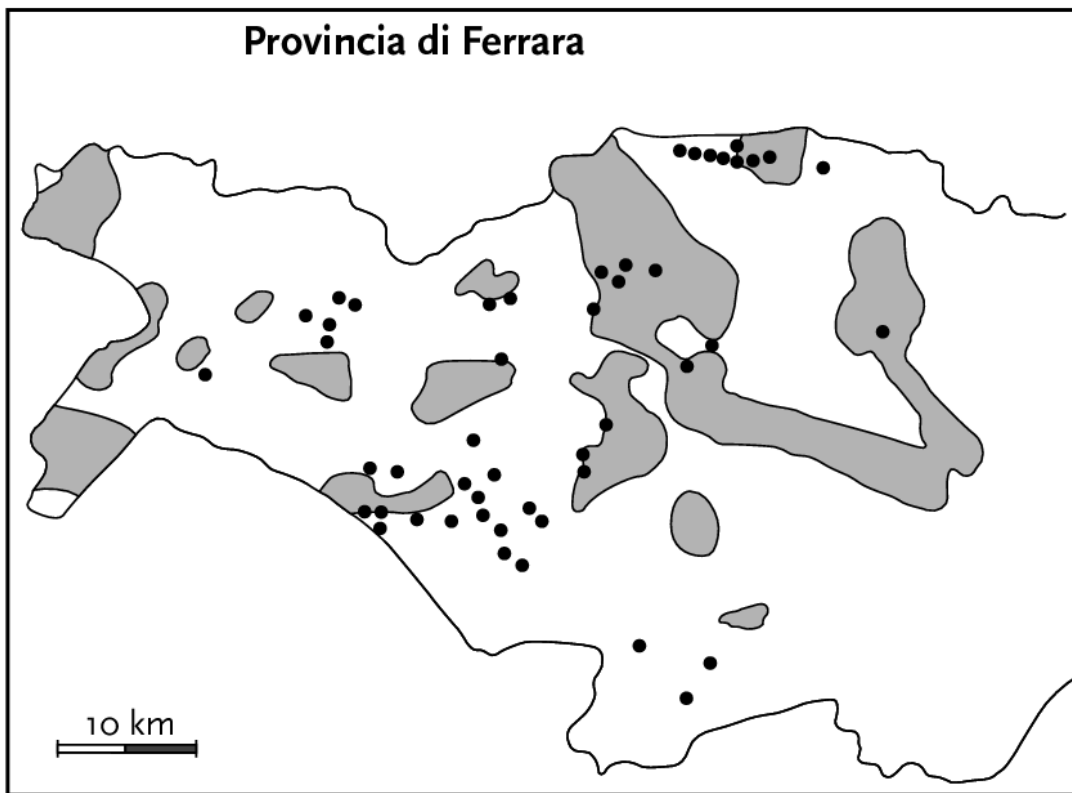


Fig. 8 Hail damage (gray area) in 1982 in Ferrara province, Italy; the dots are 49 hail cannon locations (BENINCASA et al., 1991).

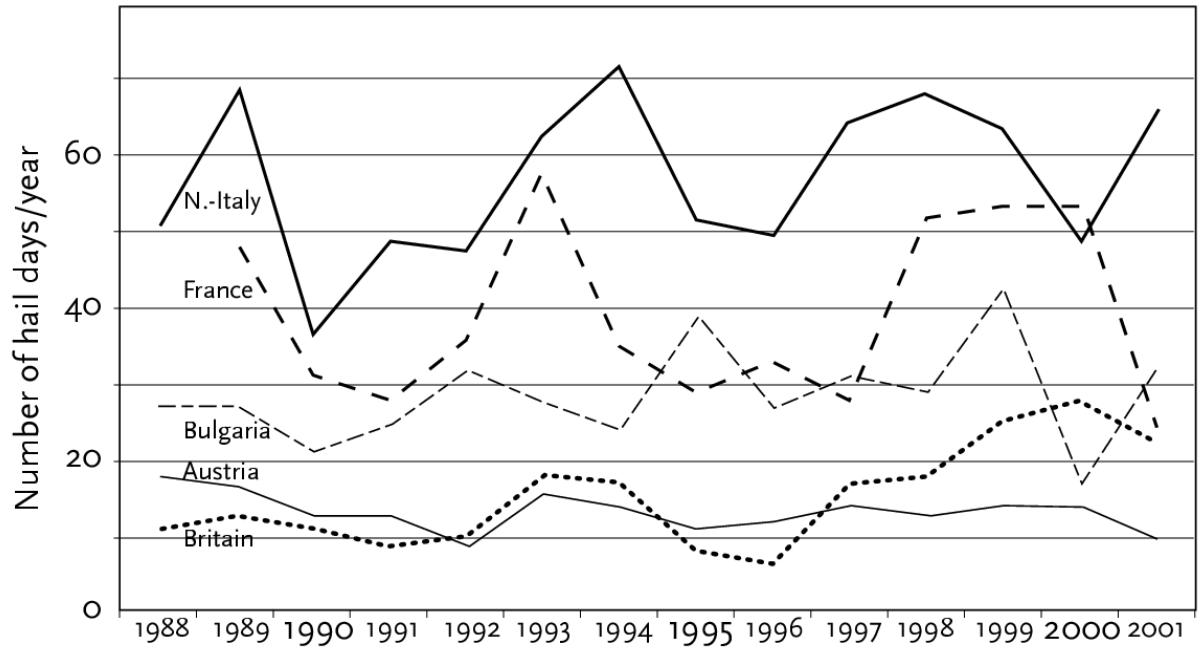


Fig. 9 Long-term variability of hail in Europe (GIAIOTTI et al., 2003).

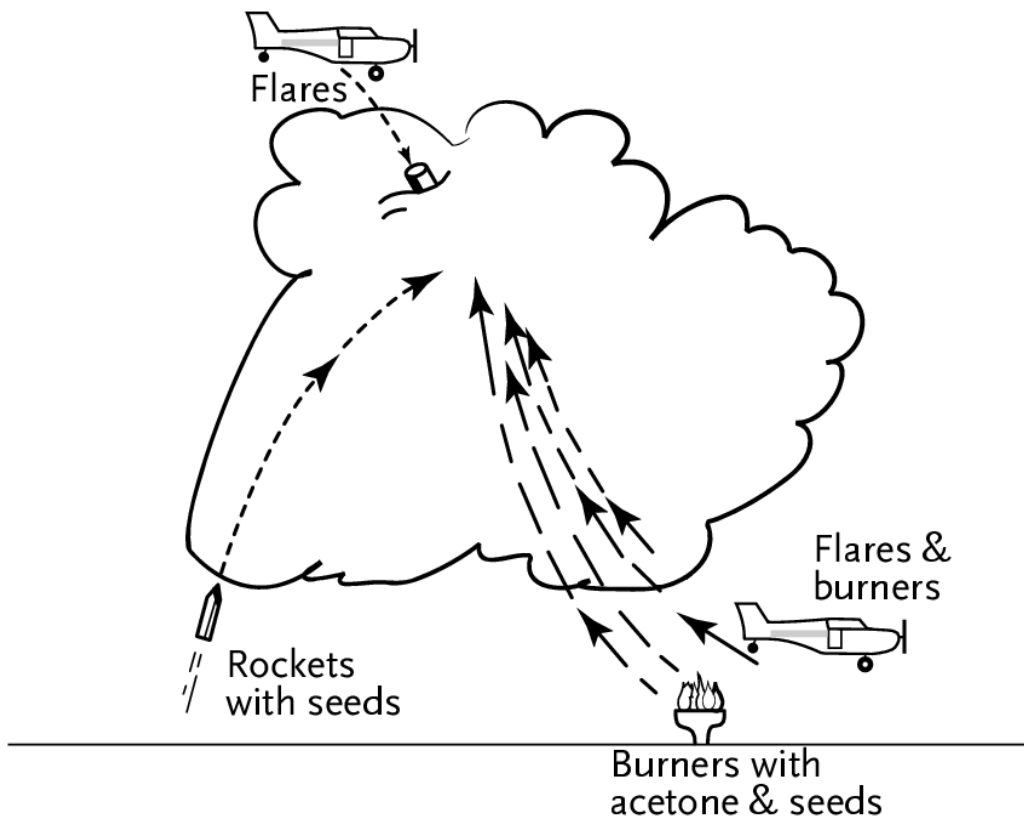


Fig. 10 Alternative ways to seed a cumulus cloud



Fig. 11 An AgI burner surface station in Robion (Vaucluse, France).

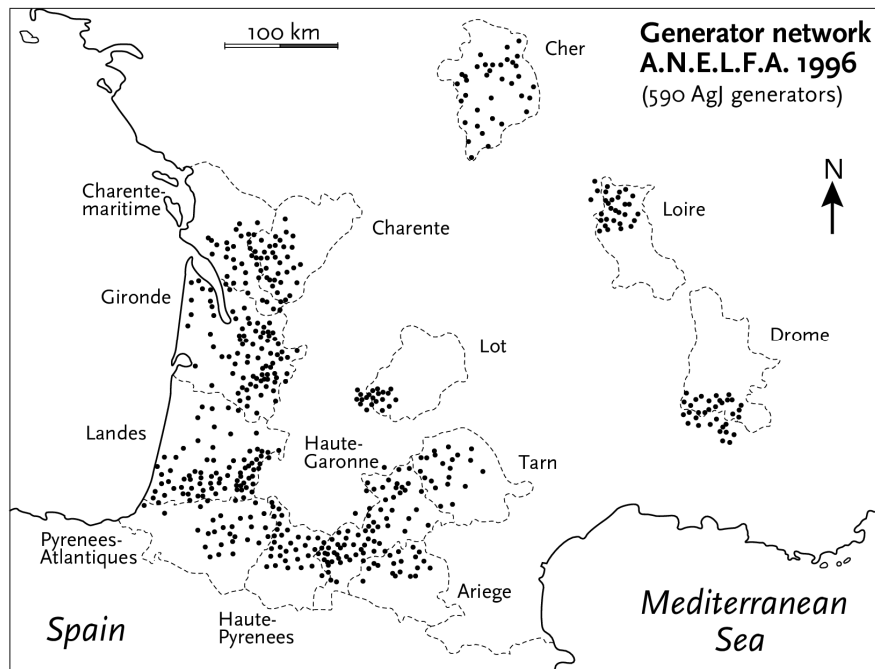


Fig. 12 Network in southern France of 590 AgI burner surface stations, as organized in 1996 by ANELFA (Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques, anelfa@anelfa.asso.fr).